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Bezeichnung: Piezoelektrischer Transformator mit Cu-Innenelektroden

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Die angehefteten Stücke sind eine richtige und genaue Wiedergabe der ursprünglichen Unterlagen dieser Patentanmeldung.

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Piezoelektrischer Transformator mit Cu-Innenelektroden

The present invention relates to multilayer piezoelectric transformers comprising a lead zirconate titanate, $Pb(Zr_x Ti_{1-x})O_3$ or PZT, ceramic body and internal Cu electrodes, and to a method of producing such transformers.

Piezoelectric transformers have been invented in 1954 by Rosen et al. (U.S. Patent 2,830,274). The principle of their operation is to convert first electrical input into mechanical vibrations of the body of a transformer and subsequently to reconvert the energy of mechanical vibrations back to an electrical output signal. The two-fold energy conversion occurs through piezoelectric effect. The transformer action, i.e. the voltage step-up, is accomplished by utilizing properties of ceramic materials, such as mechanical quality factor, Q_m, and electromechanical coupling coefficients, k_{ij}, and a structure of the transformer, such as distance between electrodes in its primary and secondary parts.

Since that time a large number of technical papers have been published and a large number of patents have been issued throughout the world, which aimed at developing (i) new designs of piezoelectric transformers, (ii) new piezoelectric materials for application in

transformers, and (iii) electronic circuits which incorporate piezoelectric transformers. In particular, multilayer piezoelectric transformers were developed, which consist of piezoelectric ceramics co-fired with internal metaI

electrodes. The benefit of multilayer design is a possibility to increase voltage step-up ratio by controlling the distance between internal electrodes in the primary or in the secondary part. Thus for a given voltage step-up ratio, the size of transformer can be reduced by using multilayer design.

Such a strong interest to piezoelectric transformers is explained by the belief that these components can substitute electromagnetic transformers in many applications, first of all where comparatively low power, below 20 W, and a small size of transformer is required. Such applications include (i) backlight inverters for liquid crystal displays in lap-top computers and recently in hand-held organizers, video and photo-cameras, (ii) electronic ballast for fluorescent lamps, and (iii) AC/DC converters for cell phones, laptops and other rechargeable hand held devices.

The following advantages of piezoelectric transformers over electromagnetic are mentioned:

(i) high power density of piezoelectric material, which allows to build a compact transformer with smaller dimensions, in particular a smaller thickness, than those of electromagnetic transformer;

(ii) low energy loss, and therefore a higher efficiency of transformer. Unlike electromagnetic transformers, piezoelectric transformers do not have wiring in the primary and secondary parts, and therefore are free of the losses related with wiring, such as loss due to eddy current and skin effect in metal;

(iii) higher reliability. which is related with a reduced risk of short circuit between primary and secondary parts due to the absence of wiring;

(iv) piezoelectric transformers do not generate electromagnetic noise, and therefore do

not interfere with adjacent circuitry that can be sensitive to the magnetic field

Despite the above mentioned technical benefits of piezoelectric transformers, electromagnetic transformers have one significant advantage: low production cost due to the large scale production over a long period of time, which is noticeably lower than the fabrication cost of multilayer piezoelectric transformers. Comparatively high production costs of piezoelectric transformers is determined to a larger part by the cost of expensive metal electrodes, which are typically made of Pt or Ag/Pd-alloy. Such expensive metals are required for co-firing with PZT ceramics at high temperatures, between 1100°C and 1200°C. which are necessary to fabricate dense PZT ceramics with good properties, such as high piezoelectric coupling coefficients.

In order to be able to co-fire piezoelectric ceramics with electrodes made of inexpensive metals, such as Ag or Cu, one has to reduce the firing temperature of ceramics below the melting point of the metal, which is equal to 1085°C for Cu and 962°C for Ag. In addition to that, if one uses Cu electrodes, the firing must be carried out in the inert atmosphere, in order to avoid oxidation of Cu. Co-firing of ceramics with Ag electrodes can be carried out in the oxidizing atmosphere (air).

At present, reference can be made to the following four publications, which deal with co-firing of piezoelectric ceramics with Cu or Ag electrodes

There are two publications, which describe the method of the firing of piezoelectric ceramics at 900°C, in particular the method of producing multilayer piezoelectric transformers with internal Ag electrodes. In US patent 5,792,379, the firing at 900°C was achieved by mixing PZT ceramics with a specially prepared glass frit composed of combination of B_2O_3, Bi_2O_3, CuO and same other metal oxide, such as ZnO, BaO, etc.

In the other patent application WO 200121548, the firing at 900°C was achieved by mixing PZT ceramics with a combination of $Bi_2O_3$and CdO, which has a low melting temperature, and therefore assists the densification of PZT ceramics. It has been claimed that the advantage cf using $Bi_2O_3$and CdO, instead cf glass frits, was that both Bi and Cd can be incorporated in the crystal lattice of PZT, and therefore should not form undesired secondary phases which can be detrimental to the properties of ceramics. In both works, a dense ceramics was obtained by firing at 900°C.

However, the ceramics described in both patents had poor properties, in particular comparatively law values of electromechanical coupling coefficient, k_p = 0,45-0,47, mechanical quality factor, Q_m = 500-650, and dielectric constant, ε_{33} = 400-550. The law values of these material parameters can result in poor characteristics of the transformer, such as a low voltage step-up ratio, low power and low efficiency. Such poor properties of ceramics may be

the consequence of the firing of ceramics at low temperature 900°C. Namely at low temperatures,, the grain growth could be restricted, and low diffusion rates could not provide a homogeneous distribution of Zr and Ti in the crystal lattice of PZT.

With this in mind, co-firing with Cu electrodes may be seen as a better technological option to fabricate multilayer piezoelectric transformers with high performance, because higher firing temperature, 1000°C instead of 900°C, should result in PZT ceramics with superior properties.

References can be made to two patent applications which describe co-firing of multilayer piezoelectric ceramic components with internal Cu electrodes. One of them, DE 19946834-A1, describes multilayer piezoelectric actuator with internal Cu electrodes and the method of producing the same. It is described that it is possible to fabricate multilayer piezoelectric actuator with internal Cu electrodes, however no specific details are presented as to how to achieve that.

Another patent application, DE 10062672-A1, describes multilayer piezoelectric components with internal Cu electrodes and the method of producing the same. First, this application describes in detail the method of co-firing of piezoelectric ceramics with internal Cu electrodes, which results in a components of high density and having a good performance. Second, it relates to multilayer piezoelectric components in general, which may imply multilayer transformer as well. The method of producing such components is described for multilayer piezoelectric actuators.

The major difference between piezoelectric actuators and piezoelectric transformers is that the former, in particular actuators described in DE 10062672-A1, are made of so-called "soft" piezoelectric ceramics. "Soft" piezoelectric ceramics is obtained by doping basic composition $Pb(Zr_x Ti_{1-x})O_3$ with a few mole % of donor additives, which are high-valency cations, such as Nd^{3+} substituted for Pb^{2+}, as described in the patent application DE 10062672-A1. "Soft" piezoelectric ceramics is distinguished by high values of piezoelectric charge coefficient, d_{ij}, and dielectric constant, ε_{ii}, but at the same time by high dielectric and mechanical losses, which are represented by tan δ and reciprocal mechanical quality factor, $1/Q_m$, respectively. High mechanical losses imply low mechanical quality factor, Q_m. In particular, PZT ceramics doped with Nd has tan $\delta > 2\%$ and $Q_m = 50\text{-}70$. Such values are inappropriate for application in piezoelectric transformers, because such transformers will have a low efficiency.

Piezoelectric transformers are typically fabricated using a "hard" piezoelectric ceramics. "Hard" ceramics is obtained by doping the basic composition, $Pb(Zr_x Ti_{1-x})O_3$, with a few mole % of acceptor additives, which are low-valency cations, such as Mn^{2+}, Fe^{2+}, Ni^{2+}, Zn^{2+}, Mg^{2+} , Li^{1+} {substituted for Zr^{4+} or Ti^{4+}) or Ag^{1+} (when substituted for Pb^{2+}). "Hard" PZT ceramics are characterized by low mechanical ($Q_m = 1000\text{-}2000$) and dielectric (tan $\delta = 0{,}3\text{-}0{,}4\%$) losses.

Until now, all known compositions of "hard" piezoelectric ceramics have been developed for ceramics fired in the oxidizing atmosphere (air). It has not been studied until now, how the properties of "hard" PZT ceramics doped with such additives will change during firing in the inert atmosphere. The patent application DE 10062672-A1, teaches

how to fabricate the "soft" piezoelectric ceramics only. It is possible that co-firing in the inert atmosphere might be detrimental to the piezoelectric properties of "hard" PZT ceramics, which might make the ceramics not suitable for application in piezoelectric transformer.

The present invention describes multilayer piezoelectric transformer, which is made by co-firing "hard" piezoelectric ceramics with internal Cu electrodes. The use of Cu electrodes must substantially reduce the production cost of the transformer, which should make them more competitive on the market. This should be considered as a major improvement compared to multilayer transformers co-fired with Ag/Pd or Pt internal electrodes.

The present invention has an advantage over technology, where multilayer piezoelectric transformers are fabricated with internal Ag electrodes. in that higher temperature of co-firing, 1000°C against 900°C, results in ceramics with superior properties. This is because higher temperatures promote grain growth and a more homogeneous distribution of Zr and Ti in the crystal lattice of PZT.

Compared to the existing technology of multilayer piezoelectric transformers, the invention is the use of Cu electrodes which are co-fired with "hard" piezoelectric ceramics.

Processing method from powder to the co-firing ot ceramics with Cu electrodes has been adopted from patent application by EPCOS, DE 10062672-A1. Compared to that work, the present invention has a novelty that it uses "hard" piezoelectric ceramics, instead of "soft" ceramics described there.

Multilayer piezoelectric transformers with internal Cu electrodes have been successfully fabricated. The transformers have different designs, including different shape and different electrode layout. Until now only transformers of one design have been characterized. The characteristics of the transfcrmers have met the requirement of the application in AC/DC converter, for which this transformer has been designed,

The composition of ceramics has a general formula $Pb(Zr_x Ti_{1-x})O_3 + y\ Pb(Mn_{1/3} Nb_{2/3})O_3$. This composition is known in the prior art and has properties that are suitable for application in piezoelectric transformers. The design of the transformer, including electrode layout may be chosen as needed for the application of the customer, for which this transformer has been fabricated. The processing route, including removing of an organic binder and a control of inert atmosphere during firing is described in the patent application DE10062672-A1.

The invention uses the steps of firing of "hard" PZT ceramics in the inert atmosphere at 1000°C leads to the density of ceramics which is higher than that of ceramics with the same chemical composition, but fired at 1000°C in the oxidizing atmosphere, eg. air. The possibility to obtain "hard" PZT ceramics with high density by firing it in the inert atmosphere simplifies fabrication process of the transformer, because no additives, such as those described in the prior art are required now. Those additives were developed in order to reduce the firing temperature of ceramics in the oxidizing atmosphere, e.g. air.

The firing in the inert atmosphere improves the properties of "hard" piezoelectric ceramics which are of crucial importance for application in piezoelectric transformers. In particular, dielectric losses become smaller and electromechanical coupling coefficient increases compared to those of ceramics with the same chemical composition which was fired at 1000°C in the oxidizing atmosphere (air).

Patentansprüche

1. Piezoelektrischer Transformator mit mindestens zwei Keramikelementen aus einer $Pb(Zr_x\ Ti_{1-x})O_3 + y\ Pb(Mn_{1/3}\ Nb_{2/3})O_3$ enthaltenden Zusammensetzung und einer zwischen den zwei Keramikelementen angeordneten Elektrode, bei dem die Elektrode Kupfer enthält.

2. Transformator nach Anspruch 1, das aus keramischen Grünfolien hergestellt ist, welche einen thermohydrolitisch abbaubaren Binder enthalten.

3. Transformator nach Anspruch 2, bei dem der Binder eine Polyurethandispersion ist.